© ISTOCK

Climate Change, Technology, and Sustainability

A. M. HASNA

Digital Object Identifier 10.1109/MTS.2010.939226

Climate change controversies have raised the profile of sustainability discussions. Increased attention has yielded greater understanding of climate change as a global environmental problem, one that requires global cooperation and greater scientific consensus in order to reduce carbon emissions and consequently our energy footprint.

Climate change, technology, and the sustainability debate are inseparable in a general sense, since sustainability is the capacity to maintain a certain process or state. Sustainability is also time dependent. Climate change and sustainability also are new domains that need be better understood by engineers. Engineers recognize that sustainability means being economically viable, ecologically sound, socially responsible, and culturally appropriate. Yet, these aspects fail to address the importance of "technology" as an element of the climate change and sustainability debate. The term "technology" in this context implies any system that humans may use to modify nature to meet their needs and wants.

Increased Attention

It is now widely recognized that the Earth does not have an infinite capacity for absorbing human industrialization. At the same time, whether one is deeply concerned with, or skeptical about, climate change, it is generally agreed that economic growth is necessary. This is true in the western world, but of even more concern in the developing world where growing populations should be entitled to their share of wealth and happiness [1].

Montgomery [2] described how soil erosion led the fall of civilizations from Mesopotamia to Rome, a circumstance often related in these cases to poor irrigation. Similarly, if humans today reflect on these lessons from history we will find that the significance of engineering technologies today in the climate change debate is colossal. Sustainability cannot be addressed separately from technology. A common example of engineering technology relates to carbon dioxide (CO_2) being one of the main contributors to human-induced global warming, warming that is accelerated by the burning of fossil fuels and deforestation. The more we burn, the more greenhouse gases are produced. The natural variation for our planet as a system means that the Earth may not be able to recover from its own losses.

Hence, climate change questions lately are often coupled with the concept of sustainability. Generally, an accepted aim is to achieve a balance among the three aspects of sustainable development: economic, environmental, and societal [3]. However we live in a world captured, uprooted. and transformed by the titanic economic and techno-scientific process [4]. In the words of [5], engineering, as an element of technology as a social process, is changing the world [6].

The idea that technology and applied sciences are essentially tools to understand and master the world was formulated much earlier by René Descartes (1596–1650) [7]. More modern research in the field of science and technology studies has gathered much evidence that science is not separate from society and that it does not just discover uncontested "truths" that are then translated into policies [8]. On the contrary, [9] critiqued modern technological society, not just technology but the larger, impersonal methods and "systems" by which our family, social, and political lives are ordered.

> Technological change compliments societal change and vice versa.

Relationship Between Engineering and Technology

So what is the relationship between engineering and technology? A number of good reviews exist on the distinction between science, engineering, and technology. For the purpose of this discussion, science is defined as the principal laws of the natural world, tested over time and validated; engineering is the process of applying scientific principles to benefit society; and technology is the products and processes created by engineers to benefit society. Engineering has been central to the great economic growth that has characterized the rise of industrial capitalism, and as we move into a knowledge-based economy engineering remains a fundamental element [10]. Engineers are creators of technology [11] through the

> Sustainability cannot be addressed separately from technology.

application of scientific principles, design, and construction, defines engineering.

Similarly technology is directly related to economics. Johnson and Wetmore [12] reported on the entwined nature of technology in engineering and in society. They explained that although efficiency appears as the only engineering necessity imposed on all human activity, making informed decisions about technology is not simply a process of maximizing benefits and minimizing problems. The importance of the engineering sciences and technology in driving sustainable economic and social development and addressing basic needs, including the reduction of poverty, was emphasized at the World Conference on Science in 1999, the World Engineers' Convention in 2000, the Johannesburg World Summit on Sustainable Development in 2002, and WEC 2004 – "Engineers Shape the Sustainable Future." Those discussions also relate directly to the UN Millennium Development Goals.

Technologies "evolve" to solve problems perceived by various relevant social groups. Hence contemporary society, science and technology are inseparable. According to Weber [13], cultures are characterized by the presence of numerous techniques. These concepts are validated by the birth of recent literature on social construction of technology (SCOT) studies [14]–[21]. Out of all this, numerous contentious philosophical debates have arisen over many issues related to the use of technology in society, from debates over technology benefits and drawbacks, concerns about dilution of privacy, to worries about the influence of the Internet upon children [22]. Given that technology is often a consequence of science and engineering, we need to start with a updated definition of technology.

Defining Technology

Modern society is full of technology, and technology's benefits to modern society are numerous. However, technology is not neutral; it reflects cultural values. Technology includes the many tools, techniques, materials, and sources of power that humans have developed to achieve their goals. Technologies are often developed in response to specific task requirements using practical reasoning and experiential knowledge [23].

Technology is also a broad concept. It can be described as a cultural and institutional phenomenon [24], [25]. There are different ways of conceptualizing technological innovation and technological change in society, "innovation" is often synonymous with technology. Technological innovation is defined "the commercial application of human or machine embodied know-how that results in new, or previously unapplied technological changes to, products or processes. Technological innovations are further separated into radical and incremental forms" [26]. Similarly technological development or innovation may be described as a continuing evolutionary process of variation and selection [27]. Let us list some definitions of technology:

- The practical application of technical knowledge [28].
- The process by which humans modify nature to meet their needs and wants [29].
- A multiphasic, multilevel input/output mechanism that is interdependent with its environment; an excellent overview in [30] notes that technology derives structure instead of adapting to existing structure.
- An activity that forms or changes culture [31]
- The means by which outputs are created [32]

In addition, technology is discussed in [32]. However, it is the definition of technology in [33]—as the transformation of inputs into outputs—that links technology to consumptionism. Finally not all technology developed has had a net positive outcome; for example, did the creation of a nuclear bomb benefit society? Probably not. However, technologies need to be developed in order to harvest associated better technological benefits. Touching on the critical issue of nuclear technology leads us to consider armament and warfare technology. What about warfare in general, or pollution, or deforestation? These situations developed from engineered technologies that arguably do more harm than good.

Society and Technology

Society is becoming even more dependent on engineering and technology [34]. At a macro level, technology has been described as the major engine of economic growth [35]. Without technology, it would not be possible to sustain the present human population on this planet. Moreover, without technology, the human population could never even have grown to anything near its current level. Technology is intertwined with society's progress.

Critiques of technological sustainability originated in the 1960s and 1970s [36]. This theory was advanced by in [37]. However, Kidd suggested that the roots of sustainability in a broad sense originated from six separate strains, but we do not intend to describe each of these, except for technology. The reason is that information technology lies at the root of productivity and economic growth [38]. Alan

Greenspan, former Chairman of the U.S. Federal Reserve, noted that economic development in the first decade of the 21st century emphasized the essence of information technology and digital society in the expansion of knowledge [39]–[41]. However, a digital society implies dependence on networked ICT's, with more people using the Internet, cell phones, digital video, digital music, personal computers, etc. Therefore, a digital society implies reliance on electricity in supporting 21st century socio-economic development [42]. But electricity traditionally relies on natural resources, irrespective of the generation methods.

Even when renewable energy resources are being exploited, some degree of natural resource dependence remains. For example, hydro-electric generation requires a water supply and solar requires sunlight. Renewable resources mitigate, but cannot eliminate entirely, our dependence on natural resources. Benefits of ICT information and communication technology (adapted from [26]) include:

- These technologies can be used to compete against monopolistic trends.
- They can accelerate innovation reduce cycle times.
- They have an unprecedented capacity for the dissemination of knowledge and information.
- They are a major driver of the globalization process.
- They play an important role in making science research more efficient.

Let us now review technology in the context of the Russian economist Kondratieff's 1925 cyclical activity long-waves theory: "Major Economic Cycles." According to Kondratieff, capitalist societies rise in long waves of approx. 50–60 years. Each cycle consists of three phases: expansion, stagnation, and recession. In his theory a new cycle arises from the ashes of the previous cycle and thus the process repeats itself. Evidence for this theory is shown in Table I and Fig. 1.

Table I
Approximate Timing Kondratieff Waves

1) Industrial Revolution	1780s–1840s
2) Steam Power and Railways	1840s–1890s
3) Electricity and Steel	1890s–1940s
4) Mass Production ('Fordism')	1940s–1990s
5) Microelectronic and Computer Networks	1990s–current

Innovation develops incrementally due to demand from markets, from the substitution of old technologies by new technologies, and from the combination of existing technologies into new combinations. We can see these trends in Astronomy, Evolution, Medicine, Chemistry, and Earth Science. In addition to technological progress within disciplines, technology can also encourage inter-disciplinary work.

Some inventions trigger a wave of new innovations. When this phenomenon occurs, the triggering invention is known as a "Big Bang event." [43] Such events result in an S-curve jump, as shown in Fig. 1.

In order for an invention to trigger a Big Bang, it must have a broad effect in several different applications. For example, GPS navigation in motor vehicles was only possible because of advances in electronic components and telecommunications.

Fig. 1 lists several technologies that had a dramatic impact in multiple applications. These technologies extend our ability to organize and control. But a burst of innovation does not continuously generate new ideas; instead, technologies advance in cycles, alternating periods of variation, competitive selection, retention or convergence [44]. Examples of inventions that produced such cycles include antibiotics, plastics, semi conductors, Insulin, the personal computer, and the Internet.

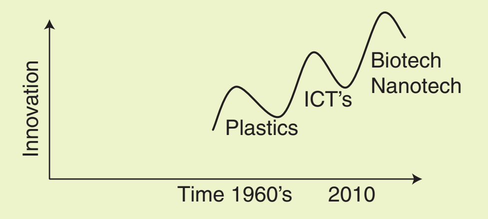

Fig. 1. Waves of innovation.

Sometimes innovations in one area are dependent on progress in another area. For example, the widespread use of all-electric automobiles will require improved electric generation and transmission infrastructure. Another example is the research in material substrates that may dramatically improve HD DVD technologies.

Engineers and Technology

The fundamental role of engineers and technology in the economic and politic arena has direct relationship with the perception of our natural resources. In the late 1990s, for instance, the world largest economy, the United States, deliberated on these issues, through the White House at the time, as follows: Science helps us to understand the origins, characteristics and consequences of global problems. Finding solutions to these problems, and elucidating the complex chains of cause and effect through which they may be linked, requires a coordinated effort by natural and social scientists, engineers, and policy-makers. As science plays an ever-increasing role, however, Even when renewable energy resources are being exploited, some degree of natural resource dependence remains.

scientists must remain true to the fundamental principles of objectivity and impartiality. Transforming scientific breakthroughs into new technologies can have a profound impact on development, but wise stewardship of these technologies is essential. One challenge of sustainability is to use technology in such a way that it balances advances in productivity with long-term resource viability. For example, technology helped bring about the Green Revolution, which resulted in increased agricultural productivity worldwide [45]. But at the same time, poorly designed irrigation systems led to soil degradation in some areas. In the decades ahead, technology will be called upon to feed a growing world population, with minimum impact on the integrity of soil, water, forests, and other resources [46].

Technology Should be a Major Criterion

As engineers in society, let us examine our professional existence. How do we survive? We live in a world captured, uprooted, and transformed by the titanic economic and techno-scientific processes [4]. In a global historical context, Cohen [66] suggested four periods of evolution in human population growth, the first related to development of local agriculture (8000 BC), the second related to global agriculture (AD 1750), the third related to public health (1950), and the fourth related to fertility (1970). But it is information technology that defines the current period. According to Crump [47]–[51], whether the focus is technology, the economy, or society at large, it is widely accepted that technology will have profound effects on natural resources. According to Hargroves and Smith [52], technology develops as a response to a perceived problem, need, or desire. The waves shown in Fig. 1 illustrate the progression of technology over time, simultaneously with a maturing civil society. Development is often described in terms of successive advances in technology. For example, the steam age, the industrial age, and the information technology age all refer to different historical periods. We now live in a world that is highly reliant upon technology for food, employment, and economic prosperity. Very often several solutions are available to address a given situation. Being able to select the most appropriate technology initially can reduce the potentially disastrous social, economic, and environmental impacts that an inappropriate choice may have in the longer term.

The major sources of environmental pressures normally associated with the different components of a technology are listed in Fig. 2. The main pathways by which a technology interacts with its surroundings can normally be divided into the following categories: the material, labor, and energy resources used by the technology; the wastes and hazardous products released into the environment; and the impacts of the supporting infrastructure and services. While the environmental consequences of a technology will vary, all the components listed in Fig. 2 relate directly to climate change and sustainability. Hence, technology operating in different locations may have very different environmental impacts relating directly to sustainability. However, if we consider certain guidelines of sustainable technology [53], we determine that: the consumption of resources should be minimized, consumption chains of non-renewable materials should be closed, and there should be a preference for renewable materials and energy sources. It is impossible to satisfy all three points or any one point indefinitely without considering time constraints, hence time functions apply to all sustainable consumption scenarios. There can be "no perpetual growth."

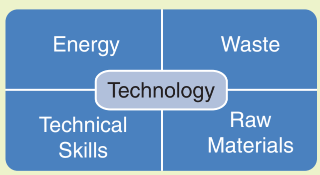

Fig. 2. Components of a technological system.

Technology must be a major criterion in sustainability assessments. Fuchs and Lorek [54] identified technology as an important determinant of sustainability. In addition, Van der Wal and Noorman [55] found that technology influences energy consumption [56], and that technology is an important source of potential reductions in energy consumption. Ferguson et al. [57] examined the relationship between total energy consumption and wealth creation and between electricity generation and wealth creation, and recommended that the benefits of electricity generation are at least of the same order of magnitude as economic development itself. The relationship between energy consumption and the gross national product (GNP) of countries has become such a commonly understood concept that figures in U.S. dollars per ton of oil equivalent (toe) are quoted as world development indicators by the United Nations. Pacey [58] tackled the idea that technological design seems to be divorced from the context of the use of products. He gives examples of big dams feeding leaking pipes and electricity generating stations pumping heat into the atmosphere when electricity is mainly used for heating, as examples of "halfway technology." Today most major car companies are taking steps to lighten their vehicles while improving their quality, to improve the efficiency of existing types of engines while reducing their unwanted exhaust emissions. This is perhaps what Alexander [59] would describe as forms that badly fit their context; fitness is the relation of mutual acceptability between domains. In a design problem, we want to satisfy mutual demands that two entities make upon one another. We want to put the context and the form into effortless contact or frictionless coexistence.

The interaction of the technology with the environment as described by Balkema *et al.* [60] is schematically represented in Fig. 3. The demands of the end user are translated into functional criteria that must be fulfilled by the technology. Hasna [61] acknowledged the importance of a financial criterion observed under a triple bottom line to assess for climate change and sustainability assessments [62]–[65]. On the other hand, the literature has limited clarity on the relationship between climate change, sustainability, and technology.

Technology Efficiency May Be Key

Technology has been discussed by sociologists and economists with varying polarity. Most notable were Adam Smith, Marcuse, and Karl Marx. Definitions of technology on both sides of the spectrum have validity equating technology's value to the quality of life. Nevertheless other negative forces, such as human enslavement or destruction of natural environments to exploit resources, are ingrained in all technological

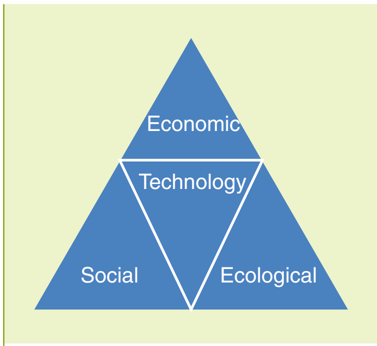

Fig. 3. Technology central to the environment.

innovations, which are limited by the physical laws that govern our universe.

Reality is likely to fall between the extremes. How can engineers play a more positive role in sustainability transformation? The sustainability debate is likely to continue on the basis of theoretical opinions and policy proposals.

The engineering profession can make significant contributions towards global aspirations for sustainability by developing inherent emission reduction technologies. The limitations of this orthodoxy are that future technology cannot be a continuation of the past philosophies of development, since it was industrialization and growth through innovation that subsequently brought the economic success that got us here. Hence in response to climate change, development of technology provides some solutions, but not the solution.

What are the risks in focusing too strongly on climate change for its own ends, rather than adequately applying technology efficiency to meet the needs of an expanding population that is expecting a higher quality of life? We argue that society is driven by growth, and growth is determined by successive technology. While traditionally, technological change has complimented societal change and vice versa, in modern society, climate change and sustainability can be synonyms of "technology."

In conclusion, we propose that technology considerations be analyzed when assessing for sustainability, since technology can also increase society's vulnerability. Some adverse effects are irreversible.

Author Information

Abdallah M. Hasna is a senior design engineer at Orica Mining Chemicals; email: ahasna@impe.com.au.

References

[1] J. Venselaar, "Sustainable growth and chemical engineering," *Chemical Engineering Technol.*, vol. 26, no. 8, pp. 868–874, 2003.

[2] D.R. Montgomery, *Dirt: The Erosion of Civilizations.* London, U.K.: Univ. of California Press, 2007.

[3] A.A. Martins, T.M. Mata, and C.A.V. Costa, "Framework for austainability metrics," *Ind. Eng. Chem. Res.*, vol. 46, pp. 2962–2973, 2007.

[4] E. Hobsbawm, *Age of Extremes: The Short Twentieth Century 1914–1991.* London, U.K. Michael Joseph, 1994.

[5] S.L.T. Goldman, *The Social Captivity of Engineering, Critical Perspectives on Nonacademic Science and Engineering.* Bethlehem, PA: Lehigh Univ. Press, 1991.

[6] C. Mitcham, "Why Science, Technology, and Society Studies?," *Bull. Science Technology Society*, vol. 19, no. 2, pp. 128–134, 1999.

[7] D. Parrochia, "French philosophy of technology," in *French Studies In The Philosophy Of Science*. 2009, pp. 51-70.

[8] R. Grundmann, "Climate change and knowledge politics," *Environmental Politics,* vol. 16, no. 3, pp. 416–434, 2007.

[9] J. Ellul, *The Technological Society*, J. Wilkinson, transl. New York, NY: Knopf, 1964.

[10] Engineers Australia, *Issues in Relation to Innovation* in *Beyond Brain Drain-Mobility, Competitiveness & Scientific Excellence*, F.Q. Wood, Ed. Armadale, NSW, Australia: Federation of Australian Scientific and Technological Societies (FASTS). 2004.

[11] H. Christ, *Fundamentals of Engineering Ethics.* Dusseldorf, Germany: VDI the Association of Engineers, 2002.

[12] D.G. Johnson and J.M. Wetmore, *Technology and Society: Building Our Sociotechnical Future.* Cambridge, MA: M.I.T. Press, 2008.

[13] M. Weber, *From Max Weber: Essays in Sociology*, H.H. Gerth and C.W. Mills, Eds. New York, NY: Oxford Univ. Press, 1946.

[14] P. Berger and H. Luckmann, *The Construction of Reality: A Treatise in the Sociology of Knowledge.* New York, NY: Anchor, 1967.

[15] J.R. Beniger, *The Control Revolution: Technological and Economic Origins of the Information Society.* Cambridge, MA: Harvard Univ. Press, 1986.

[16] W. Bijker, T. Hughes, and T. Pinch, *The Social Construction of Technological Systems*. Cambridge, MA: M.I.T. Press, 1987.

[17] D. MacKenzie and J. Wajcman, *The Social Shaping Of Technology: How The Refrigerator Got Its Hum*. Philadelphia, PA: Open Univ. Press, 1985.

[18] D. MacKenzie and J. Wajcman, *The Social Shaping of Technology*, D. MacKenzie, Wajcman J., Eds. Buckingham, U.K.: Open Univ. Press, 1999.

[19] H.K. Klein and D.L. Kleinman, "The social construction of technology: Structural considerations," *Science, Technology and Human Values*, vol. 27, no. 1, pp. 28–52, 2002.

[20] F. Webster, *Theories of the Information Society,* 2nd ed. NewYork, NY: Routledge, 2002.

[21] A. Dafoe, "Theoretical reconciliation: Selectionism in the social construction of technology and the diffusion of (military) innovations," in *Proc. DRUID Tenth Anniv. Summer Conf. Dynamics of Industry and Innovation: Organizations Networks and Systems,* (Copenhagen, Denmark), 2005.

[22] U.M. Franklin, *The Real World of Technology*. Toronto, ON: House of Anansi, 1999.

[23] S.T. March and G.F. Smith, "Design and natural science research on information technology," *Decision Support Systems*, vol. 15: pp. 251–266, 1995.

[24] A. Balsamo, *The Technological Imagination Revisited; Designing Culture: A Work of the Technological Imagination*. Duke Univ. Press., 2005.

[25] H. Brown, *Sustainable Consumption and Production*. Worcester, MA: Clark Univ. Press, 2009.

[26] M. Hargreaves, "Innovation, collaboration, and the international firm," in *Master of Business.* Brisbane, Australia: Queensland Univ. of Technology, 2004.

[27] R.R. Nelson and S.G. Winter, "In search of a useful theory of innovation," *Research Policy and Politics,* vol. 6, no. 1, pp. 36–76, 1977.

[28] C. Weiss, "Science, technology and international relations," *Technology in Society,* vol. 27, no. 3, pp. 295–313, 2005.

[29] NAE, *What is Technology?* 2007.

[30] D.M. Rousseau, "Assessment of technology in organizations: Closed versus open system approaches," *Acad. Management Rev.*, vol. 4, pp. 531–542, 1979.

[31] A. Borgmann, "Technology as a cultural rorce: For Alena and Griffin," *Canadian J. Sociology*, vol. 31, no. 3, pp. 351–360, 2006.

[32] R.M. Marsh and M. Hiroshi, *Technology and Size as Determinants of the Organizational Structure of Japanese Factories.* JSTOR, 1981, 26.

[33] M.E. Burkhardt and D.J. Brass, "Changing patterns or patterns of change: the effects of a change in technology on social network structure and power—Technology, organizations, and innovation," *Administrative Sci. Quart.*, vol. 35, pp. 104–127, 1990.

[34] C.U. Chisholm, "Critical factors relating to the future sustainability of engineering education," *Global J. Engineering Education*, vol. 7, no. 1, pp. 29–37, 2003.

[35] J. H. Dunning, "Location and the multinational enterprise: A neglected factor?," *J. Int. Business Studies*, vol. 29, pp. 45–66, 1998.

[36] S. Bell and S. Morse, *Sustainability Indicators: Measuring the Immeasurable?* London, U.K.: Earthscan, 1999.

[37] E.F. Schumacher, *Small is Beautiful: A Study of Economics as if People Mattered*. London, U.K.: Blond and Briggs, 1973.

[38] L. Sterne, *Internet, Growth – Not Inflation – Define the New Century, Internet Stocks Channel Systems*, L. Sterne, Ed. Cambridge, MA: M.I.T. Press, 2000.

[39] D.A. Bromley, "Technology policy," *Technology in Society*, vol. 26, pp. 455–468, 2004.

[40] R. Lowenstein, O*rigins of the Crash: The Great Bubble and Its Undoing*. Penguin, 2004.

[41] R. Lowenstein, "How the Fed learned to love technology," *Technology Rev.*, 2005.

[42] W.S. Baer, S. Hassell, and B.A. Vollaard, *Electricity Requirements for a Digital Society*. Arlington, VA: RAND, 2002.

[43] C. Perez, "Technological revolutions and financial capital: The dynamics of bubbles and golden ages," Cheltenham, UK: Elgar, 2002.

[44] M.l. Tuchman, P.C. Anderson, and C. O'Reilly, *Technology Cycles, Innovation Streams, and Ambidextrous Organizations: Organization Renewal Through Innovation Streams and Strategic Change*, vol. 3–23. Oxford, U.K.: Oxford Univ. Press, 1997.

[45] White House, *Meeting the Challenge of Global Threats, A National Security Strategy of Engagement and Enlargement*. National Archives and Records Administration, 1995.

[46] S. Wasserman-Goodman, *The Environment and National Security*, in *Remarks as Prepared for Delivery by Deputy Under Secretary of Defense (Environmental Security)*, National Defense University, 1996.

[47] T. Crump, *A Brief History Of Science, As Seen Through the Development of Scientific Instruments*. London, U.K.: Constable and Robinson, 2001, pp. 78-81.

[48] T.R. DeGregori, *The Environment, Our Natural Resources, and Modern Technology*. Ames, IA: Iowa State Press, 2003.

[49] W.E. King, "Greenscapes and greenbuilding: integrating "engineered soils" as a stormwater best management practice in sustainable landscape construction," in *Georgia Water Resources Conf. Proc.*, H.K. J., Ed. Univ. of Georgia, 2005.

[50] S.P. Restivo, *Technology, and Society: An Encyclopedia*. Oxford Univ. Press, 2005.

[51] J.R. Kehl, "Resource security bridging the divide between energy, economy, security, politics and policy," in *Proc. ISA 49th Ann. Conv. Bridging Multiple Divides*. 2008: Hillton San Francisco, San Francisco, CA, USA.

[52] Hargroves, K. and M. Smith, *The Natural Advantage of Nations: Business Opportunities, Innovation and Governance in the 21st Century*. London, U.K.: Earthscan/James and James Pub., 2005.

[53] K. Mulder, *Sustainable Development for Engineers: A Handbook and Resource Guide*. Sheffield, U.K.: Greenleaf Pubs., 2006.

[54] D.A. Fuchs and S. Lorek, "An inquiry into the impact of globalization on the potential for 'sustainable consumption' in households," in *Workshop on Sustainable Household Consumption: Impacts, Goals and Indicators for Energy Use, Transport and Food*. Enschede, Norway: ProSus/CSTM, 2000.

[55] J. Van der Wal and K. Noorman, "Analysis of household metabolic flows," in *Green Households? Domestic Consumers, Environment, and Sustainability,* K. Jan Noorman and T. Schoot Uiterkamp, Eds. London, U.K.: Earthscan, 1998.

[56] G. Dürrenberger and P. Nikola, "Energy metabolism of Swiss households," in *Proc. Sec. Int. Symp. Sustainable Household Consumption*. Groningen-Paterswolde, 1999.

[57] R. Ferguson *et al.*, "Benefits of electricity generation," *IEEE Engineering Science and Education J.*, 1997.

[58] P. Pacey, *The Culture of Technology*. Basil Blackwell, 1983.

[59] C. Alexander, *Notes on the Synthesis of Form*. Cambridge, MA: Harvard Univ. Press, 1964.

[60] A.J. Balkema *et al.*, "Indicators for the sustainability assessment of wastewater treatment systems," *Urban Water*, vol. 4, no. 2, pp. 153–161, 2002.

[61] A.M. Hasna, "*Sustainability in engineering design," Int. J. Environmental, Cultural, Economic and Social Sustainability*, vol. 4, no. 1, pp. 19, 2008.

[62] G. Wall, "Is ecotourism sustainable?" *Environmental Management*, vol. 21, no. 4, pp. 483–491, 1997.

[63] D.J. Rapport, "Economics and ecologically sustainable futures," *Int. J. Social, Economics,* vol. 24, no. 7/8/9, 1997.

[64] M. Safley, "How traditional agriculture is approaching sustainability," *Biomass and Bioenergy*, vol. 14, no. 4, pp. 329–332, 1998.

[65] A. Saida *et al.*, "Exploring an innovative watershed management approach - From feasibility to sustainability," *Energy Policy,* vol. 31, pp. 2373–2386, 2006.

[66] J. Cohen, *How Many People Can the World Support*. New York, NY: Norton, 1995.